

## First scientific results from the Infrared Astronomical Satellite (IRAS)

B. T. Soifer and G. Neugebauer

Division of Physics, Mathematics and Astronomy  
California Institute of Technology  
Pasadena, California 91125

### Introduction

The Infrared Astronomical Satellite (IRAS) was successfully launched on 25 January 1983 and terminated science data acquisition on 22 November 1983. The in-orbit performance of the telescope has been described in two previous papers in these proceedings.<sup>1,2</sup> A previous description of very preliminary scientific results from the mission has been given in these proceedings<sup>3</sup>, while far more extensive reports have been given elsewhere<sup>4,5</sup>. In this paper we will summarize some of the results obtained to date from the IRAS data. The work to date has sampled only a small fraction of the IRAS data; the study of the data from the IRAS survey will continue for many years to come.

### Solar system studies

IRAS was the most successful comet finder in history. At the end of data acquisition IRAS had discovered six new comets in the last seven months of its life. Among these were the closest approaching comet to earth in the last two centuries (IRAS-Araki-Alcock), and a nearly dormant comet (1983 TB) that is likely the parent body of the Geminid meteor stream. With this discovery IRAS has made a significant advance in associating meteor streams with their parent bodies in the solar system.

IRAS has discovered large scale structures, described as "zodiacal dust bands", that should give us clues to the origin of the zodiacal cloud. These bands are illustrated in Figure 1, and appear as strips parallel to the ecliptic plane at  $\sim \pm 9$  degrees from the ecliptic plane. From the color temperature of these bands<sup>6</sup> and parallax measurements made on these bands half a year apart in the course of the IRAS survey<sup>7</sup>, they appear to be in the midst of the asteroid belt. Dynamically, these bands must be made of a distribution of small particles orbiting the sun, with similar inclination angles, and a uniform distribution of their lines of nodes. It has been suggested<sup>5,6</sup> that the origin of these bands is in the debris from the collisions of asteroids in the main belt. The similarity of the orbital inclination of these zodiacal bands to that of families of asteroids<sup>8</sup> has also been noted. Thus, it is possible that these bands are the result of the collision processes that made the asteroids in the prominent Hirayama families.

### Material in orbit around stars

One of the most spectacular discoveries to date from IRAS has been that of solid material, substantially larger than interstellar dust, in orbit around the nearby bright star Vega<sup>9</sup>. Subsequent to this discovery, observations were made of another nearby star, Fomalhaut, which showed it to share similar properties to Vega<sup>5</sup>. A subsequent, though not nearly as detailed, study of a much larger sample of nearby stars using the IRAS survey data has shown that approximately 10% of them show far infrared excesses similar to that found in Vega<sup>10</sup>. While the evidence for this larger sample of stars having solid material in orbit is by no means as strong as for Vega and Fomalhaut, it suggests that the agglomeration process that produced the clouds of large particles surrounding these two stars is quite common in the formation of stars.

### Old stellar systems

Because the tremendous sensitivity of the IRAS observations is most readily converted into detection of small amounts of solid particles in space radiating via their thermal emission, the IRAS observations can be used to study nearly dust free environments. One such observation, that of the globular cluster 47 Tuc<sup>11</sup>, has been used to demonstrate that the amount of dust shed by the old, dying stars in this stellar system is two to three orders of magnitude less than previously thought must be there. The lack of this material is made all the more mysterious because individual stars in this cluster are seen by IRAS to be shedding material as expected. This kind of observation illustrates that the extreme sensitivity to small amounts of dust allows the IRAS data to be used to probe for very small amounts of material in forms previously inaccessible to astronomical investigation.

### Star formation regions

One of the major goals of the IRAS mission was to identify and study the sites of active star formation in our Galaxy. IRAS has indeed found many sites of such activity. With the vast increase in sensitivity afforded by IRAS we have been able to detect the sites of formation of the lower mass stars, those of masses comparable to the sun, that are occurring within a few thousand light years of the sun<sup>12,13</sup>. Thus the IRAS survey will give us the road map to study how stars such as our own are now forming.

### The extragalactic sky

The nature of the infrared sky away from the plane of the galaxy changes substantially as one looks at longer wavelengths. At 12  $\mu\text{m}$  and 25  $\mu\text{m}$  the brightest objects in the sky are dust-embedded stars within our own galaxy, while at 60  $\mu\text{m}$  and 100  $\mu\text{m}$ , the brightest objects in the sky are galaxies, some hundreds of millions of light years distant from us that are radiating prodigious amounts of energy in the far infrared. The range of properties associated with galaxies in the infrared is huge. Characterizing the infrared activity of a galaxy by the ratio of infrared to visible luminosity emitted, we have found that this activity varies by over four decades, from those galaxies virtually undetectable in the infrared, to those that radiate well over 99% of their luminosity in the infrared.

Once again, we believe that we are seeing predominantly the thermal radiation of small dust particles warmed by the local radiation field to temperatures ranging from 20K to 60K. In the case of the galaxies that are virtually undetectable by IRAS, it has been found<sup>14</sup> that these galaxies are elliptical galaxies, i.e., old stellar systems that show no evidence of interstellar gas or dust, and consequently no evidence for current star formation activity. The lack of detectable infrared emission from these galaxies implies that they are virtually devoid of interstellar dust, which in turn leads to a problem much like that described above for the globular clusters in our own galaxy, i.e., where is the dust going that such old stars should be shedding in the process of dying.

Normal galaxies are characterized by an infrared to visible luminosity ratio of between 0.1 and 1. Figure 2 shows the visible image compared with the 60  $\mu\text{m}$  contour map of the normal spiral galaxy M31, the great nebula in Andromeda. M31<sup>15</sup> is quite characteristic of the properties of normal spiral galaxies. In this galaxy there is a small amount of infrared radiation associated with the dust and gas in the general interstellar medium, but the vast majority of the infrared luminosity in M31 is emerging from regions where we believe star formation is currently occurring in the galaxy. Indeed, we have used this association of infrared luminosity with star formation in such galaxies to generalize the relation to infer that in normal spiral galaxies the infrared luminosity measures the current star formation activity in the galaxy<sup>14</sup>.

IRAS has discovered that there is a significant population of galaxies that emit a very large fraction of their luminosity, 90% or more, in the infrared<sup>16,17,18</sup>. Figure 3 shows an example of one of the closest examples of these extreme "infrared" galaxies. This is a visible photograph of the interacting galaxy ARP 220, which was first identified as a peculiar galaxy by Halton C. Arp<sup>19</sup>. IRAS observations<sup>20</sup> have shown that this galaxy is among the 10 brightest galaxies in the sky at 60  $\mu\text{m}$ , while it is fainter than 10 to 20 thousand other galaxies in the visible. This galaxy is emitting almost 100 times more energy in the infrared than in the visible.

Not only is virtually all the energy from these galaxies emerging in the infrared, but this is an energy output far greater than that of a normal galaxy. Arp 220 is among the most extreme such galaxies that have been discovered to date. Its total luminosity is roughly 200 times that of our own galaxy and 10 times larger than the luminosities of the most luminous "normal" galaxies. Indeed, the only objects in the universe known to produce luminosities comparable to these extreme "infrared" galaxies discovered by IRAS are the quasars.

Not surprisingly, the discovery of these extremely luminous "infrared" galaxies has raised more questions than it has answered. The most obvious question is what is powering these galaxies. While there is a great deal of evidence that indicates that the infrared radiation we see from these galaxies is thermal radiation by dust, the source of energy that heats this dust is still open to question. Because the luminosities of these galaxies are so great, it is logical to consider the possibility that they are powered by quasars that are not visible to us as normal quasars. If this is the case, then these represent a class of quasar never before seen, and one which we do not understand at all.

Another possibility is that these extremely luminous galaxies are powered by a current "burst" of newly formed luminous stars. In this case, these galaxies are converting gas

into stars at a rate hundreds of times that in active star-forming galaxies like our own, and this cannot continue for more than 100 million years without involving an entire galaxy's mass of interstellar gas. Clearly, such a rapid processing of gas into stars would be a major turning point in the evolution of the galaxy. If such giant starbursts are indeed providing this luminosity, then understanding the importance of such events for these galaxies, and how they relate to the evolution of what we believe to be normal galaxies, will be a major problem for astronomers to solve for years to come.

### Conclusions

In this paper we have barely scratched the surface of the findings already revealed from the IRAS data. The analysis to date of the IRAS data has clearly demonstrated the wealth of new phenomena occurring in the universe that are accessible to astronomers through sensitive observations at infrared wavelengths. Astronomers will continue to mine the treasure represented by the IRAS data for years to come.

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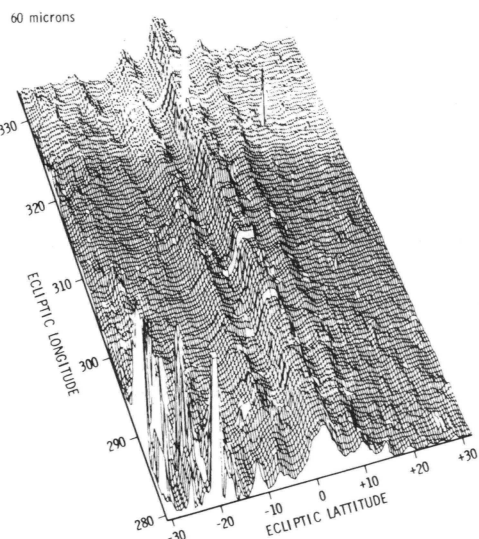


Figure 1. Illustration of the zodiacal dust bands discovered by IRAS. The data shown are  $60\mu\text{m}$  fluxes and were taken from scans across the ecliptic plane near  $300^\circ$  ecliptic longitude. The scans were spatially averaged to  $1^\circ$  resolution and high-pass filtered in the direction perpendicular to the ecliptic plane to show the zodiacal dust bands. Intensity is proportional to the height of the projected three-dimensional surface. The three dust bands are formed in the ecliptic and  $\sim 9^\circ$  above and below the ecliptic, and run parallel to the ecliptic equator.

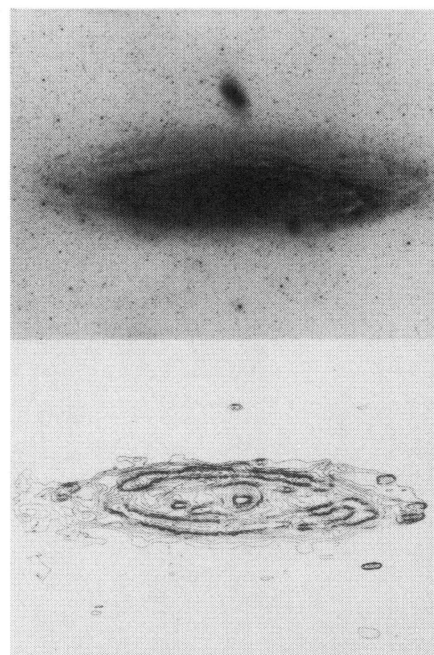


Figure 2. Comparison of the appearance of the large spiral galaxy in Andromeda (M31) in the visible and the infrared. In the visible the stars are dark and the dust lanes are light. In the contour plot of the infrared emission at  $60\mu\text{m}$  from the galaxy the dominant structure is the ring corresponding to the dust lane of the visible photograph.

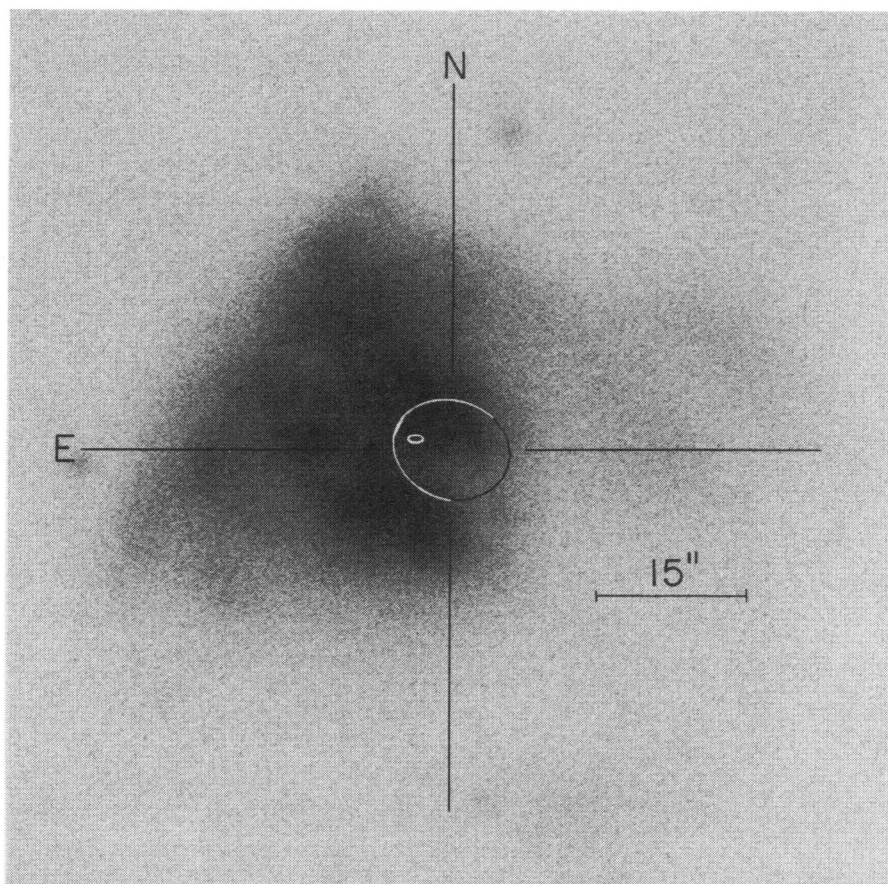


Figure 3. The visible image of Arp 220 (©1966, California Institute of Technology) that shows the spiral appearance of this extremely luminous infrared galaxy. The large ellipse is the  $1\sigma$  error ellipse of the IRAS source position, with the cross indicating the IRAS position. The small ellipse shows the radio source size at its position. The bar indicates the angular scale of the picture.